In : Lee, Jeffrey A. and Zobeck, Ted M., 2002, Proceedings of ICAR5/GCTE-SEN Joint Conference, International Center for Arid and Semiarid Lands Studies, Texas Tech University, Lubbock, Texas, USA Publication 02-2 p. 122

Measured and modeled roughness heights (Z_0) over diverse roughness elements, central Mojave Desert, California, USA

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Introduction

We are developing a wind-erosion model to investigate the sensitivity of dust-emission rates in the Southwestern U.S to climatic variability and land-use changes. Dust-emission rates largely depend on the amount that wind shear or "friction" velocity (u_*) within the boundary layer at the surface ***exceeds*** the "threshold" friction velocity of the surface (u_{*_t}) ([3]). To calculate u_*, we use an atmospheric boundary layer (ABL) model designed for terrestrial-type planets ([1],[2]). This model includes effects of "free-stream" wind velocity, atmospheric stability, both aerodynamically smooth and aerodynamically rough airflow, and the roughness lengths of momentum, sensible-heat, and water-vapor transfer (Z_{0m}, Z_{0h}, Z_{0v}). The ABL model is currently being linked with the non-hydrostatic Penn State/NCAR mesoscale climate model MM5 ([5]) to allow coupling with regional atmospheric dynamics and local topography.

Methods

The momentum roughness height (length), Z_0 (m subscript dropped) is the roughness height for a bare soil surface "covered" by non-erodible roughness elements, such as plants, clasts, and small-scale topography. As cover is removed, Z_0 approaches the roughness height of the bare surface, here noted as Z_{0s}. Z_0 also represents a measure of the rate at which the regional wind flow is dissipated through the boundary layer to overcome surface friction. The roughness height (Z_0), whether the surface is covered or bare ([6], affects ***both*** the model-derived, atmospheric friction velocity in the boundary layer (u_*) ***and*** the surface threshold friction velocity for dust-emission (u_{*_t}).

Many natural surfaces consist of a mixture of non-erodible roughness elements (e.g. plants, clasts, small-scale topography) overlying a bare erodible surface. To account for the effect of non-erodible roughness elements on the threshold friction velocity, Raupach et al. ([7]) define a term called, $R_t = (u_{*_{ts}} / u_{*_t})$ which is ratio of the threshold friction velocity for a bare erodible surface to that for a surface covered with non-erodible roughness elements. Further, Raupach et al. ([7]) were able to parameterize R_t in terms of the physical dimensions and drag coefficients of the individual surface roughness species. R_t is equivalent to the (efficient) friction velocity ratio $f_{eff}(Z_0)$ defined by Marticorena et al. (6), which is a function of the surface roughness height. Thus, Z_0, is directly connected to measurable physical dimensions and drag coefficients of the surface roughness elements.

The terms R_t and f_{eff} , however, do not account for surfaces composed of multiple, coexisting types of roughness elements (e.g., plants, clasts, and small-scale topography). To address this problem, we examine the way momentum is partitioned among arrays of roughness species, and we show mathematically (see appendix) that the total threshold friction velocity ratio, R_t , is related to the independent friction velocities of "*n*" species according to:

$$1/R_t^2 \approx (1/R_1^2) + (1/R_2^2) + \ldots + (1/R_n^2) - (n-1) \qquad (1)$$

As the total threshold friction velocity ratio, R_t , approaches values of 0.1 to 0.2 ([6]), the lee wakes behind a dominant or combination of species are packed so closely together as to completely shelter the surface against wind erosion. Aerodynamically, the wind profile characterizing this regime is displaced upward from one where bare portions of the surface still experience wind-shear stress to one whose profile represents shear stress only from the overlying roughness elements. Marticorena et al. ([6]) found that when values of Z_0 approached 0.6 cm, almost complete sheltering of the ground surface occurred. In contrast, Wolfe ([8], p.162) found that values of Z_0 approached 4 cm before complete sheltering occurred. Our measurements showed values of Z_0 up to 7.1 cm without indication of a wind-profile displacement height, although we did not place anemometers at a sufficiently low height to verify wind-profile displacement. We used this information to adjust Marticorena et al.'s ([6]) (efficient) friction velocity ratio, f_{eff} , to accommodate larger Z_0 values than 0.6 cm for complete sheltering.

This theoretical development provides a means to calculate the total roughness height of a complex surface composed of multiple roughness species and is compared below to field measurements.

Data Analysis

During one eight-day period in April 2001, we measured Z_0 at 12 diverse sites located around the perimeter of Soda (Dry) Lake, in the central Mojave Desert, California. All sites had evidence of past sand saltation, based on scouring of the surface. Three collapsible 9-meter-high wind towers were operated simultaneously at separate sites, each with three or four anemometers mounted in a logarithmic spacing with the lowest anemometer placed above 0.9 meters to protect internal bearings. One-minute averaged wind speeds were recorded from each anemometer during a 24-hour period to include the early-morning and late-afternoon periods of neutral buoyancy. We measured thermal stability from data continuously acquired at two nearby meteorological stations. Every morning the wind and thermal data were processed on-site to determine Z_0 and its associated error criteria. If the data proved sufficiently robust, a tower was moved to a new site; otherwise, the tower remained operating at the same site for another 24-hour period.

Results

While acquiring these wind data, we measured (in some cases estimated) a large number of plants for their geometrical widths, heights, and mutual separations for each surface roughness species using digital camera, tape measure, and calibrated rods. The mean and variance from these physical dimension data and estimated drag coefficients were incorporated into equation (1) as part of the Raupach parameterization of the friction velocity ratio for a particular species. Because methods are lacking to accurately measure the drag coefficients for naturally occurring solid and porous roughness elements in terms of physical parameters, estimates and uncertainties (standard deviations) for the drag coefficients were made based on previous reported field and lab studies in the literature (e.g., [4], [9]). These data were placed into equation (1) for each site and converted to calculated mean and standard deviation values of Z_0. The results, comparing the measured and calculated values of Z_0 for each site, are shown in Table 1 and plotted in Figure 1. Considering the inherent uncertainties in measuring the properties of natural systems, the results (correlation coefficient is 0.845 for mean values) show the measured and calculated values are generally within each other's standard deviation about the mean (-s, +s), which is generally considered to be a strong correspondence. Results that showed the greatest disparity could be ascribed to inadequate documented of the physical dimensions and distributions of non-erodible roughness elements, incorrect estimates of species drag coefficients, or to inadequacies in the model. More work needs to be done to test the functional form of the model (Eq. 1).

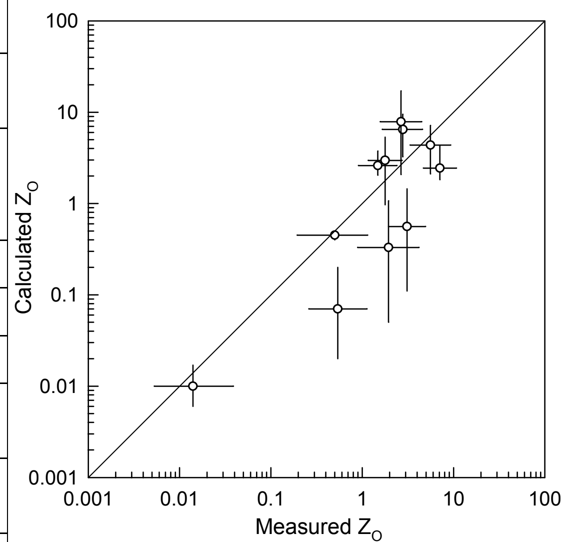
Conclusions

Our most important conclusions are: (1) the actual sheltering caused by multiple, coexisting types of roughness elements (e.g. multiple plant species, desert pavement, and small-scale topography) needs to be unambiguously defined to yield an accurate measure of the local surface roughness, $Z_{0;}$ (2) the effects of transitions from non-sheltered to sheltered surfaces may be abrupt and have a strong influence on accurate assessments of roughness element properties; and (3) the sensitivity of our Z_0 development to roughness properties suggests that during drought, surfaces largely sheltered by plants can become vulnerable to wind erosion resulting from very small losses in vegetative properties, not easily detected by the eye (e.g., substantially lower drag coefficients as a result of a relatively minor leaf loss or minor bending over of tall grasses).

Because our Z_0 development shows such a sensitive response to measured roughness geometry and drag coefficients, it would be useful to make more accurate field measurements of these properties than we achieved during our field experiments in April 2001.

Table 1. Comparison of measured and calculated mean Z_0 with added standard deviations (-s, +s) for a given site. The measured and calculated standard deviation values show skewness, because they depend on a basically logarithmic relationship.	Figure 1. Graph of measured and calculated data in Table 1 using a logarithmic scale. Correlation coefficient r=0.845 explains 71% of variance; w/site #203 removed r=0.87 explains 76% var.

Site #	Measured Z_0 (cm)			Calculated Z_0 (cm)		
	-s	Mean	+s	-s	Mean	+s
200-201	1.66	2.79	4.6	3.25	6.47	9.5
202	.89	1.94	4.2	.05	.33	1.07
203	.26	.54	1.13	.02	.07	.2
204	1.94	3.10	4.96	.11	.56	1.45
205	1.57	2.66	4.49	2.08	7.86	17.13
206	3.35	5.59	9.33	2.11	4.36	7.16
207	.91	1.48	2.4	2.04	2.6	3.76
208	.0053	.014	.039	.006	.010	.017
209	1.16	1.78	2.73	.97	2.97	5.32
210	4.68	7.1	10.78	1.82	2.44	4.28
211	.1941	.29-.71	1.15	.40	.45	.48



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